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Differences between near-surface equivalent temperature and temperature trends for the Eastern United States Equivalent temperature as an alternative measure of heat content

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Abstract

There is currently much attention being given to the observed increase in near-surface air temperatures during the last century. The proper investigation of heating trends, however, requires that we include surface heat content to monitor this aspect of the climate system. Changes in heat content of the Earth's climate are not fully described by temperature alone. Moist enthalpy or, alternatively, equivalent temperature, is more sensitive to surface vegetation properties than is air temperature and therefore more accurately depicts surface heating trends. The microclimates evident at many surface observation sites highlight the influence of land surface characteristics on local surface heating trends. Temperature and equivalent temperature trend differences from 1982–1997 are examined for surface sites in the Eastern U.S. Overall trend differences at the surface indicate equivalent temperature trends are relatively warmer than temperature trends in the Eastern U.S. Seasonally, equivalent temperature trends are relatively warmer than temperature trends in winter and are relatively cooler in the fall. These patterns, however, vary widely from site to site, so local microclimate is very important.

Keywords: climate change; heating trends; near-surface air temperature; moist enthalpy; equivalent temperature; microclimate

1. Introduction

There is currently much interest in inadvertent anthropogenic climate change (NRC, 2005). Near-surface air temperature (T) is one of the main metrics used to assess this change, as summarized in the 2005 NRC report. Estimates of globally-averaged T trends are that T has increased by 0.3–0.6 °C over the past century (Hansen and Lebedeff, 1987; Jones, 1988; IPCC, 1990; Vinnikov et al., 1990; Jones, 1994; IPCC, 1996; IPCC, 2001). There have been numerous studies of T trends (e.g. Karl et al., 1988, Jones, 1995; Hurrell et al., 2000; Mann and Jones, 2003; Peterson, 2003; Parker, 2004; Soon et al., 2004). Much attention has been given to T data because of the length of record of the surface data and since the surface is where humans conduct most of their daily activities (Hurrell et al., 2000).

By itself, however, T is an incomplete measure of warming or cooling (Pielke et al., 2004). This study investigates near-surface heating/cooling but focuses not only on T but also the heat content of near-surface atmospheric moisture. We support the application of "*moist enthalpy*" to monitor surface heating trends, in order to account for not only T changes but also heat content

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Fig. 1. Locations of surface observation sites.

changes associated with atmospheric moisture changes. Moist enthalpy is defined as

$$H = C_p T + Lq, \quad (1)$$

where C_p is the specific heat of air at constant pressure, T is temperature, L is the latent heat of vaporization, and q is the specific humidity. Specific humidity can be calculated from measurements of relative humidity, dew point temperature or wet bulb temperature (Rogers and Yau, 1989; Davey, 2005).

To facilitate the comparison between T and H, it is useful to divide Eq. (1) by C_p to obtain the equivalent temperature

$$T_E = \frac{H}{C_p}. \quad (2)$$

For the remainder of this article, we will be comparing T and T_E. Changes in T_E will better represent surface air heat content changes than T during the annual cycle in vegetation greenup and senescence in the midlatitudes and for longer-term vegetative trends such as the reforestation, and the accompanying changes of tree species composition, which have been reported over large areas in the eastern United States (Birdsey and Heath, 1995). Moisture trends can influence heating trends at or near the surface, including precipitation trends with time, both in terms of spatial distribution and precipitation intensity. In response to increasing T, surface water bodies will also tend to experience more evaporation, which will affect near-surface moisture and thus T_E. Overall, T_E trends should be relatively larger than T trends in magnitude, since T_E is directly accounting not only for sensible heating but also trends in heating driven by changes of near-surface atmospheric moisture. Site microclimates will, however, influence these relationships.

2. Data and methods

To explore the use of T_E as a metric for monitoring heating trends, this study looks at trend differences between T and T_E for surface sites in the eastern half of the

Table 1
Case study sites

City	Site #1	Site #2
Oklahoma City, OK	Tinker Air Force Base	Will Rogers World Airport
Miami, FL	New Tamiami Airport	Homestead Air Force Base
Minot, ND	Minot Air Force Base	Minot International Airport
Washington, DC	National Airport	Fort Belvoir, Virginia

Table 2
Land cover classes from the National Land Cover Dataset (NLCD — Vogelmann et al., 2001)

Land Cover Class	Description
1	Deciduous forest
2	Evergreen forest
3	Mixed forest
4	Grassland
5	Shrubland
6	Row crops
7	Small grains
8	Pasture/hay
9	Urban
10	Water
11	Other- ice/snow, bare surfaces, wetlands, orchards

Table 3
Annually-averaged 1982–1997 differences between T_E and T trends (and standard errors), with associated Z test statistic values testing whether or not the trend differences are significantly different from zero

Significance level	$\Delta T_E - \Delta T$ (°C/decade)	Z ($\Delta T_E - \Delta T$)
All trends	0.021 ± 0.004	4.88
>90%	1.068 ± 0.190	5.62
>95%	1.475 ± 0.289	5.10
>99%	1.910 ± 0.582	3.28

Trend difference significance >90% if $|Z|>1.65$, significance >95% if $|Z|>1.96$, and significance >99% if $|Z|>2.58$). Computations are done for all individual trends and individual trends that are significant at or above the 90%, 95%, and 99% significance levels. Each station is weighted equally in each mean computation.

Table 4
Test statistic values for seasonally-averaged (winter, spring, summer, fall) differences between T_E and T trends, 1982–1997, for all individual trends and individual trends that are significant at or above the 90%, 95%, and 99% significance levels

Season	All trends	>90%	>95%	>99%
Winter (JFM)	6.14	5.14	4.05	2.27
Spring (AMJ)	6.62	3.53	2.69	0.58
Summer (JAS)	7.24	4.70	6.67	7.74
Fall (OND)	−7.09	−5.10	−4.08	−4.58
Annual	4.88	5.62	5.10	3.28

Annually-averaged values are shown for comparison. Significance criteria are identical to those specified in Table 3.

United States (Fig. 1) that are included in the International Surface Weather Observations (ISWO) dataset, developed at the National Climatic Data Center in Asheville, North Carolina (NCDC, 1998). The ISWO dataset covers the years 1982–1997, has undergone extensive quality control, and consists of observations taken every 3 h. Despite its short time span, the ISWO dataset is one of the only near-surface air temperature datasets which also has pressure and humidity observations, both of which are needed to calculate T_E. In addition, this time span is adequate for investigating trend differences between T and T_E rather than their actual trends. In this investigation, a primary emphasis has been given to variations of temporal trend differences between T and T_E as a function of land cover. Data from only the eastern U.S. were considered to minimize effects of topography and because land cover data were readily available for surface sites in that region (Vogelmann et al., 2001).

Daily means of near-surface air temperature (T), dew point temperature (T_d), station elevation (z), and sea level pressure (p_o) were computed for each ISWO station. Monthly means were then computed from the daily data. From the monthly mean value for p_o, an approximation of the actual monthly mean pressure was calculated at each site, using the formula

$$p = p_o e^{-z/h}, \quad (3)$$

where z represents the elevation of the surface observation station and h is the scale height. Once p was obtained, the monthly mean specific humidity (q) and the mean equivalent temperature (T_E) were calculated (Davey, 2005).

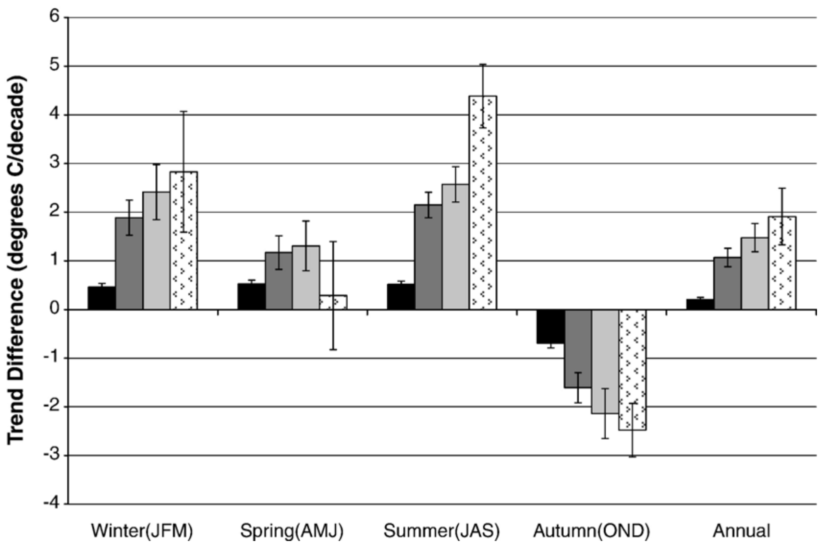

Fig. 2. Seasonally-averaged 1982–1997 differences between T_E trends and T trends for all individual trends (black bars), individual trends that are at least 90% significant (dark gray bars), individual trends that are at least 95% significant (light gray bars), and individual trends that are at least 99% significant (stippled bars). Error bars indicate standard errors. For each computation, each station is weighted equally.

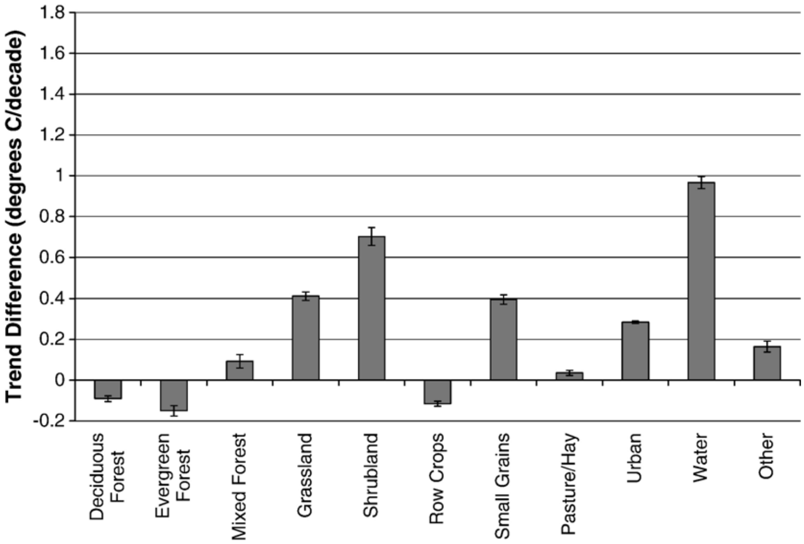

Fig. 3. Annually-averaged differences between T_E and T trends for 1982–1997, as a function of the land cover classes listed in Table 2. Error bars indicate standard errors. All individual trends are considered.

The monthly values of T and T_E were then used to contruct 1982–1997 time series of each variable. For each surface station, 24 time series were analyzed, 12 series for each variable (T, T_E). For each variable, one time series was constructed for each month of the year (e.g. the January time series consists of the values for January 1982, January 1983, …, January 1997). It is not clear that the ISWO dataset has undergone homogenization adjustments, such as the implementation of ASOS (e.g. McKee et al., 2000). A homogenization adjustment was attempted by correcting the dew point temperature and pressure values used to compute T_E for both ASOS (Automated Surface Observing System) and AWOS (Automated Weather Observing System) station commission dates, wherever applicable. Temperature was not considered in this adjustment scheme since we are focusing on differences between T_E and T trends, thus causing any T influences to be mostly cancelled out. A large majority of ASOS commission dates were after about 1995, leaving only about 1 or 2 years of data in the post-ASOS period for each station. Therefore, a correction factor was determined for that station change. Once annual averages were computed both for the year before and the year after each commission date, the post-commission annual average was differenced from the pre-commission annual average to obtain the correction factor for that station change. This correction factor was then applied to all the data after the station change date. Due to incomplete metadata on HO-83 commission dates, no attempt was made to correct for HO-83 implementations.

For each time series the 1982–1997 trend was estimated using a basic linear regression model, accounting for temporal autocorrelation.

$$y = \beta x + \varepsilon, \tag{4}$$

where β is the trend and ε is the error. The ratio of the trend estimate, b, to the standard error of the trend estimate, SE(b), given by

$$\tau = b/\mathrm{SE}(b), \tag{5}$$

is distributed as Student's t and is used to determine whether or not an estimated trend b is significantly different from zero.

The Yule–Walker (YW) method (Gallant and Goebel, 1976) is a commonly used estimation method used for

Table 5
Test statistic values for both annually-averaged and seasonally-averaged differences between T_E and T trends (1982–1997) as a function of the land cover classes in Table 2

Land cover class	Annual	JFM	AMJ	JAS	OND
Deciduous forest	−0.66	0.71	0.10	0.79	−2.70
Evergreen forest	−0.58	1.49	0.35	0.98	−2.85
Mixed forest	0.28	0.34	−0.25	2.13	−1.33
Grassland	2.05	−0.05	2.18	3.17	−0.51
Shrubland	1.60	2.17	2.45	0.84	−0.60
Row crops	−0.95	1.12	0.92	−0.55	−3.10
Small grains	1.72	−0.12	1.13	3.04	−0.24
Pasture/hay	0.28	1.21	1.84	0.98	−2.95
Urban	4.92	5.68	5.90	6.41	−5.02
Water	3.28	2.67	3.17	3.15	−0.99
Other	0.62	1.39	1.40	0.69	−1.38

Significance criteria are identical to those specified in Table 3. All trends are included in these calculations.

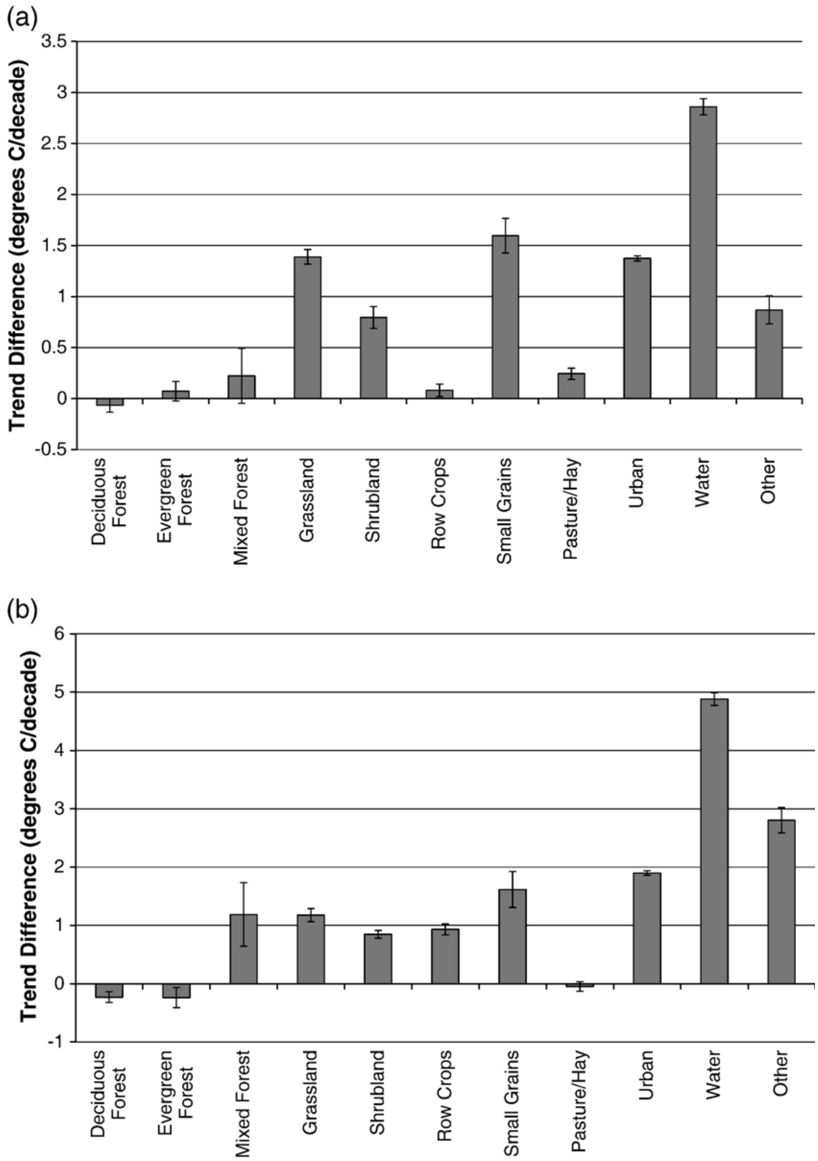

Fig. 4. Same as in Fig. 3, but for individual trends that are at least 90% significant (a) and individual trends that are at least 95% significant (b). All stations in these computations are weighted equally.

the autoregressive error model and has been used here. To obtain a best estimate for the actual trend β, first, an ordinary least squares estimate of β is found. Next, the autoregressive parameter vector is estimated, also providing an initial estimate of the variance. This cycle then repeats itself as necessary until a best estimate of β is obtained. Once this best estimate is obtained, a t-ratio (Eq. (5)) is then computed for the trend estimate to determine whether or not this estimate is significantly different from zero.

The SAS/ETS® software package was used to compute the T and T_E trend estimates. Trend estimates were computed for only those time series having at least 10 available data points (years) and the trend estimates accounted for autocorrelations covering up to four time intervals (i.e. lag-4), which means that any autocorrelations out to 4 years were corrected for in this analysis. This choice for the maximum lag interval was intended to remove most influences from interannual correlations.

Once the T and T_E trend estimates were computed, summary statistics were computed for the entire surface dataset for both T and T_E. These summary statistics were then compared with each other using null hypothesis significance testing (NHST; Devore, 1995) to determine

Table 6
Test statistic values, for annually-averaged differences between T_E and T trends (1982–1997) as a function of the land cover classes in Table 2

Land cover class	All trends	>90%	>95%
Deciduous forest	−0.66	−0.10	−0.25
Evergreen forest	−0.58	0.07	−0.13
Mixed forest	0.28	M	M
Grassland	2.05	1.95	1.06
Shrubland	1.60	0.74	M
Row crops	−0.95	0.13	1.00
Small grains	1.72	M	M
Pasture/hay	0.28	0.44	−0.06
Urban	4.92	5.40	4.96
Water	3.28	3.59	M
Other	0.62	0.63	M

Calculations are made for all trends and for those trends that are significant at or above the 90% and 95% significance levels. Significance criteria are identical to those specified in Table 3. Missing values, indicated by "M", are for those averages where the sample size was less than 10.

Table 7
Test statistic values for annually-averaged q trends (1982–1997) as a function of the land cover classes in Table 2

Land cover class	All trends
Deciduous forest	−2.39
Evergreen forest	−1.10
Mixed forest	0.67
Grassland	3.99
Shrubland	2.55
Row crops	−2.70
Small grains	3.21
Pasture/hay	0.72
Urban	9.40
Water	4.61
Other	0.87

All trends are included in these calculations.

whether or not there was a significant difference between the overall T and T_E trends (Davey, 2005). Although a diversity of procedures exist to examine such statistics, the NHST approach is adequate for this study. Comparisons were first done on an annual basis (i.e. including all observations throughout the year) and then on a seasonal basis (i.e. January–March, April–June, etc.). All stations were weighted equally in each of the mean computations.

Much attention has been given to the influences of site microclimate on T (e.g. Gallo, 1996, 2005). This study expands on this previous work to investigate differences between T and T_E trends for individual sites (Table 1). The variability of these trend differences as a function of land use/land cover was examined. Each station's primary land cover was determined using the land cover classes listed in Table 2. These land cover classes were obtained from the National Land Cover Dataset (NLCD - Vogelmann et al., 2001) for the conterminous United States, at grid increments of 1 km. The predominant land cover category for each station was determined for a 3-km × 3-km area (9 grid cells, or 9 km^2) grid of cells centered on the station of interest, by finding which land cover has the largest proportion of cells in that area. Once each station's primary land cover was determined, stations were grouped into common land cover categories. Summary statistics for the T and T_E trend differences were then computed and compared for each land cover category.

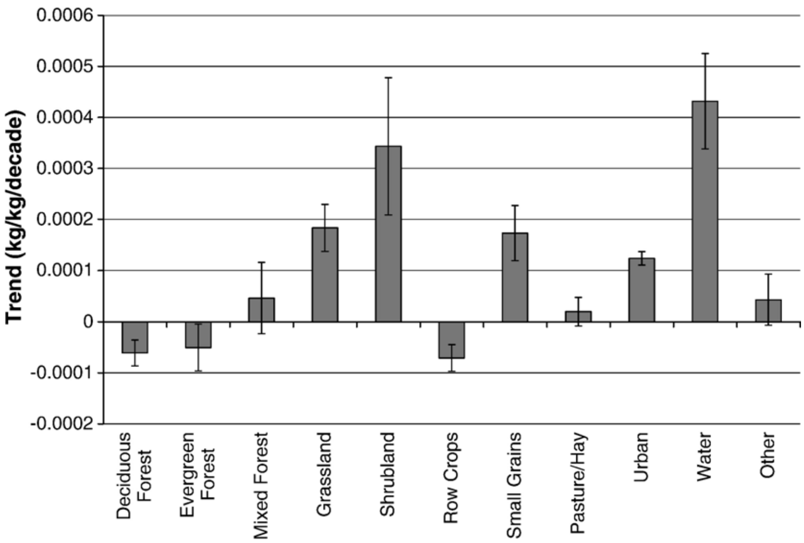

Fig. 5. Annually-averaged q trends for 1982–1997, as a function of the land cover classes listed in Table 2. Error bars indicate standard errors. All individual trends are considered and are weighted equally.

3. Trend differences between T and T_E

3.1. Annual and seasonal patterns

When a straight average (all stations weighted equally; mentioned in Section 2) is computed for the trend estimates of all stations over all seasons, the difference between the T_E and T trends is positive and significant at over 99% (Table 3). When one only averages over those trends which are significantly different from zero at the 90% level or higher, there continues to be positive $\Delta T_E - \Delta T$ trend differences as for when all stations are considered.

Seasonally, in general, the annual cycle indicates a transition from T_E trends showing significantly more warming/less cooling than T in the winter and early spring, to significantly more cooling/less warming in the fall months (Fig. 2, Table 4). The preceding results were for the case where all trends are considered. These same patterns are present when the analysis is narrowed to look only at those individual trends that are significantly different from zero at a specified significance level. As the trend significance increases, however, the difference between the averaged T and T_E trends becomes less significant during the winter and spring months (Table 4).

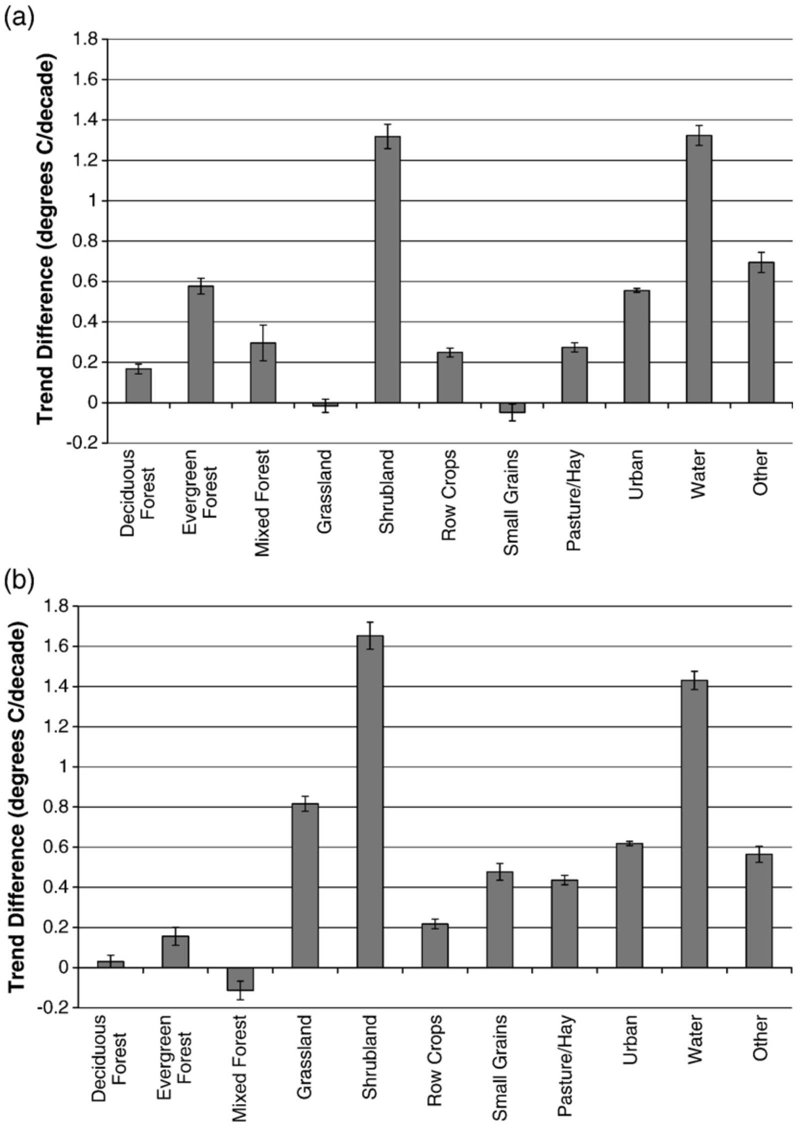

Fig. 6. Seasonally-averaged differences between T_E trends and T trends for 1982–1997, as a function of the land cover classes listed in Table 2, for (a) winter — JFM, (b) spring — AMJ, (c) summer — JAS, and (d) fall — OND. Error bars indicate standard errors. For each of these computations, all stations are weighted equally.

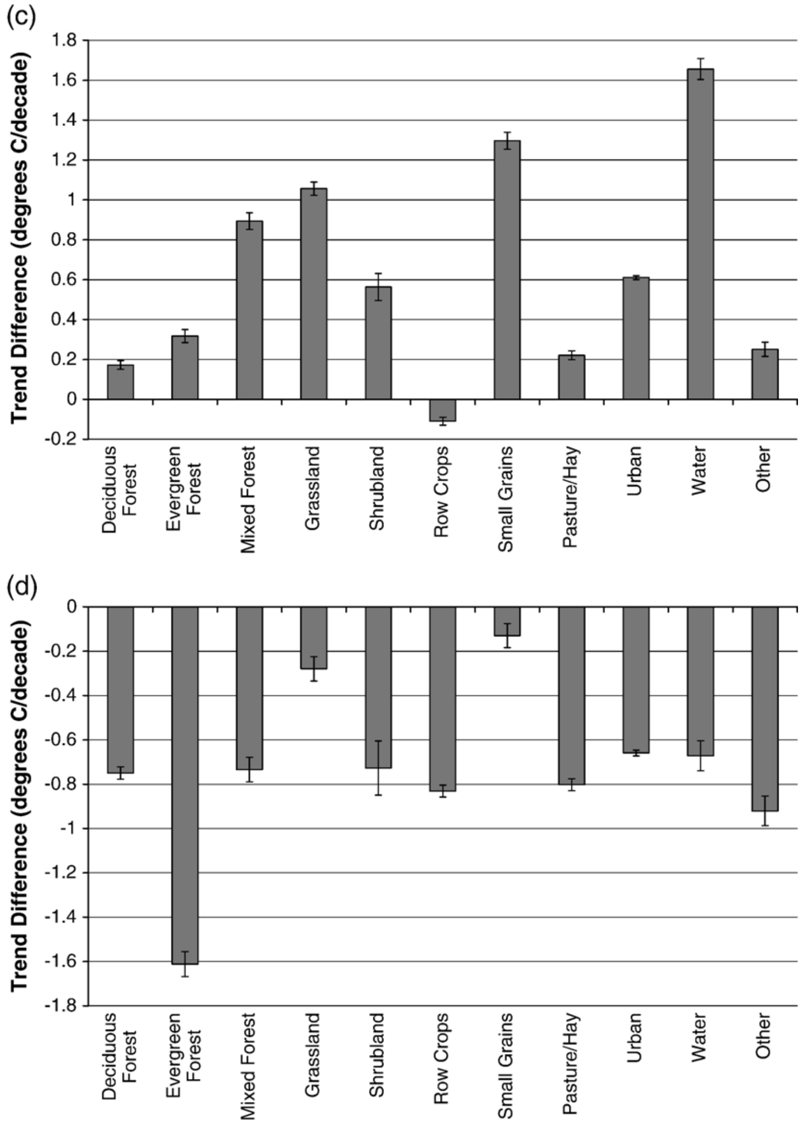

Fig. 6 (*continued*).

3.2. Land use/land cover influences

The averaged trend differences between T and T_E were then compared to see how they vary as a function of land cover, using the land cover classes listed in Table 2. As Davey and Pielke (2005) have illustrated, there are a wide variety of microclimates encountered at surface weather stations around the United States. The equivalent temperature at any given site is closely connected to the surface energy balance at that site, which in turn depends on the site's microclimate. The land cover of a surface observation site is a primary factor in describing that site's microclimate (Pielke et al., 2000, 2002; Pielke, 2003).

On an annual basis, sites whose predominant land cover is forest tend to show no significant difference between the averaged T and T_E trends. Generally, T_E trends are cooler than their respective T trends, with the most significant differences occurring for deciduous forests (Fig. 3, Table 5). Grassland and shrubland sites tend to show T_E trends that are significantly warmer than T trends. This difference is significant at above 90% for shrubland sites and above 95% for grassland sites. Sites that are predominantly agricultural have the same tendencies as that of forest sites, in that the T_E and T trends are not significantly different from each other. The exception to this is that the difference between the T and T_E

(a)

9	10	9
9	10	9
10	10	9

(b)

9	1	9
9	9	1
1	1	1

Fig. 7. Land cover characteristics for National Airport (a) and Fort Belvoir, Virginia (b), using the land cover classifications in Table 2. Each cell has a resolution of 1 km.

(a)

9	9	8
9	9	8
9	4	4

(b)

4	4	4
9	9	4
9	4	4

Fig. 9. Same as in Fig. 7, but for Tinker Air Force Base (a) and Will Rogers World Airport (b).

trends is significant at above 90% (T_E trends warmer than T) for small grains sites. Both urban sites and sites close to major water bodies indicate relatively warmer trends in T_E compared to trends in T, with the differences being significant at over 99%. The land cover class labeled as "Other" (see Table 2) shows no significant differences in T_E and T trends. Overall, T_E trends are significantly warmer than T trends for the predominantly grassland and shrubland sites, while for the predominantly forested and agricultural sites, the T_E trends are either similar or slightly cooler than the T trends.

If one only includes individual site trends that are significantly different from zero, as trend significance increases, the overall patterns for averaged heating trends (Fig. 4, Table 6) show T_E trends that are very similar to or warmer than T trends. The largest differences are observed for water sites.

These trend differences are further illustrated by the corresponding annually-averaged trends in specific humidity (q) for these land cover classes (Fig. 5, Table 7). Decreases in q (corresponding to drying) have been observed over the 1982–1997 period for row crops and both deciduous and evergreen forests. All other classes show increasing trends for q (corresponding to moistening). For those sites where q has decreased with time, the T_E trends have correspondingly shown more cooling/less warming than the T trends, since there is a decreasing amount of heat content due to atmospheric moisture over time. The opposite is true for those land cover classes where q has increased over time, with T_E trends showing more warming/less cooling than the corresponding T trends.

Fig. 6a shows that during the winter months, all land cover classes but grasslands and small grains indicate relatively warmer T_E trends than their respective T trends (also see Table 5). The land cover classes showing

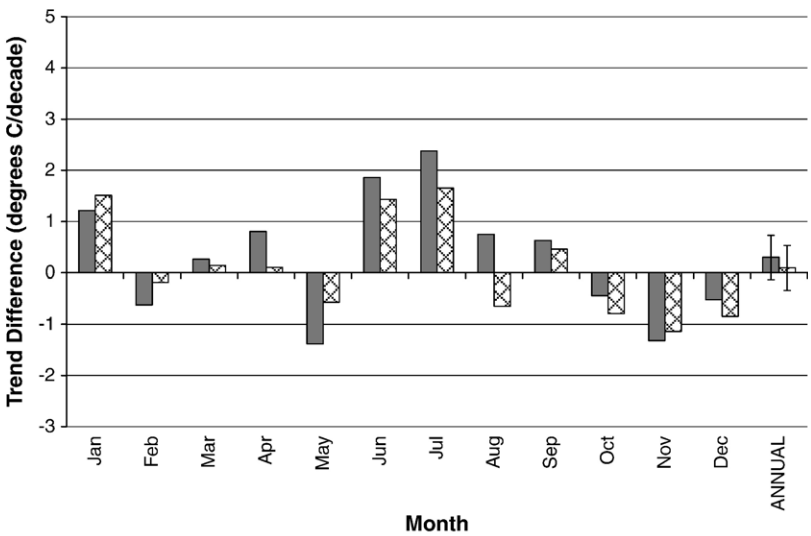

Fig. 8. $\Delta = T - \Delta T_E$ trend differences during 1982–1997 for National Airport (grey bars) and Fort Belvoir, Virginia (cross-hatched bars). Error bars indicate standard errors.

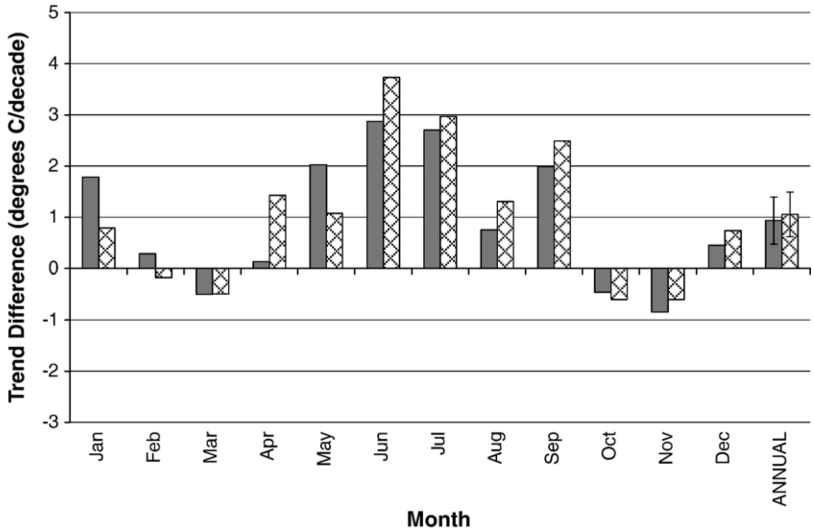

Fig. 10. Same as in Fig. 8, but for Tinker Air Force Base (grey bars) and Will Rogers World Airport (cross-hatched bars).

differences between the T_E and T trends that are significant above 90% are the shrubland sites, the urban sites, and the water sites. Moving into the spring months (Fig. 6b, Table 5), the differences between the averaged T_E and T trends are significant (T_E trends significantly more warming than T trends) for grassland sites, shrubland sites, sites with pasture/hay agriculture, urban sites, and water sites. Most of the other land cover classes indicate insignificant trend differences between T and T_E. The summer months (Fig. 6c, Table 5) indicate that, with the exception of row crop sites, T_E trends generally show more warming/less cooling than the respective T trends. Significant differences are found for mixed forests, grasslands, small grains sites, urban sites, and water sites. The T_E trends are generally cooler than T trends during the fall season (Fig. 6d, Table 5), with these differences being significant for most forest and agricultural sites. The differences between the T and T_E trends are also significant for urban sites.

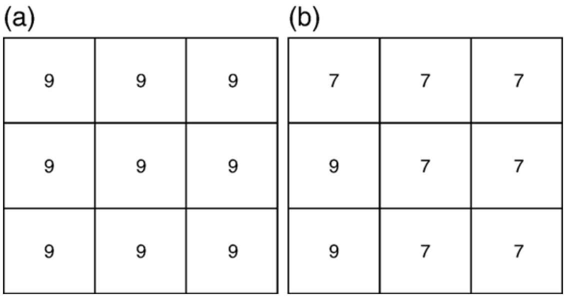

Fig. 11. Same as in Fig. 7, but for Minot Air Force Base (a) and Minot International Airport (b).

3.3. Case studies

The results from selected surface observation sites are now presented. The first sites to be considered are in the greater metropolitan area of Washington, District of Columbia. National Airport is situated on the west bank of the Potomac River, just west of the Capitol district. The land cover grid for this site (Fig. 7a) shows that urban areas (land cover #9) are present on the east and west sides of the site, with a north-south strip of water running up the middle of the site (the Potomac River). Nearby Fort Belvoir is predominantly a deciduous-forest site (land cover #1), with deciduous forests indicated primarily on the southern and eastern portions of the site. Urban land cover is present on the site's northwestern quadrant (Fig. 7b).

At both sites, the overall seasonal variations in trend differences are similar (Fig. 8). Mixed differences between T_E and T trends are observed in the winter and spring, T_E trends are relatively warmer during the summer, and T_E trends are relatively cooler during the fall. Although the spring and early summer months generally show T_E trends that are relatively warm compared to T trends, in contrast, May shows T_E trends that are relatively cooler than T trends for both sites.

The next sites we consider are located in Oklahoma City, Oklahoma. At Tinker Air Force Base, on the south-eastern side of the city, urban land covers dominate throughout the middle and western portions of the site, while grassland (land cover #4) is present at the site's south and east edges and pastures (land cover #8) dominate the northeast edges (Fig. 9a). The rural site is at Will

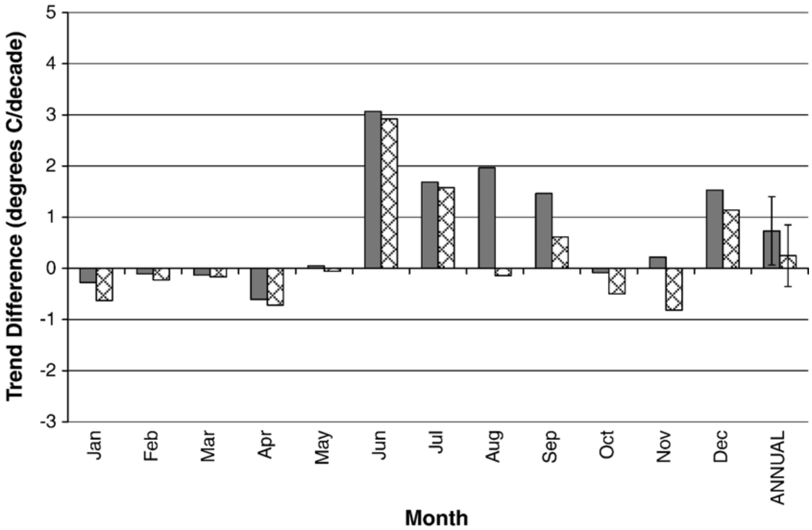

Fig. 12. Same as in Fig. 8, but for Minot Air Force Base (grey bars) and Minot International Airport (cross-hatched bars).

Rogers Airport on the city's southwest side. Urban land covers are present on the southwest edge of the Will Rogers Airport site, but grassland rings the site's north, east, and south edges (Fig. 9b).

A comparison of the annual cycle of trend differences for Oklahoma City (Fig. 10) and Washington (Fig. 8) reveals some similar patterns. To be more specific, winter and early spring show mixed differences, the summer shows T_E trends that are relatively warmer, and fall shows T_E trends that are relatively cooler than T trends. For Oklahoma City, however, the period of time in the spring and summer for which T_E trends are relatively warm compared to T trends which is more pronounced, while the period of relatively cooler trends for T_E in the fall is smaller.

Minot, North Dakota, is also located in a grassland environment, large tracts of which have been converted to agricultural production of small grains such as wheat. Minot Air Force Base is almost exclusively urban (Fig. 11a) as every cell in the site grid is so classified. The site at Minot International Airport (Fig. 11b) has a small amount of urban land cover on its southwestern edge. Everything else, however, is covered with small grains agriculture (land cover #7).

The seasonal patterns for the Minot sites (Fig. 12) have some unique characteristics compared to the previous two cities. First, the T_E trends are not relatively warmer than the T trends until the early summer months. Second, the fall months do not strongly indicate that the T_E trends are relatively cooler than the T trends.

Finally, we consider two sites located on the southwestern edge of Miami, Florida. One site is the Miami/Kendall New Tamiami Airport near Kendall, Florida, and is characterized by urban land covers over all but its eastern sectors (Fig. 13a). Water (land cover #10) is present in the southeast sector, with row crops (land cover #6) in the east sector and other miscellaneous land cover to the northeast (land cover #11). The other site is at Homestead Air Force Base in Homestead, Florida. This site has extensive row crops everywhere except the northwest sector, which is urban (Fig. 13b).

The annual cycle of the $\Delta T_E - \Delta T$ trend differences (Fig. 14) at both sites show that T_E trends are relatively warmer during the winter and spring months but then become relatively cooler during the late fall. The December trends for Homestead Air Force Base were not available for this analysis. Compared to the eastern United States as a whole, however, the peak of the warm $\Delta T_E - \Delta T$ differences occurs earlier, towards the spring months rather than the summer months. The cool differences in the fall are

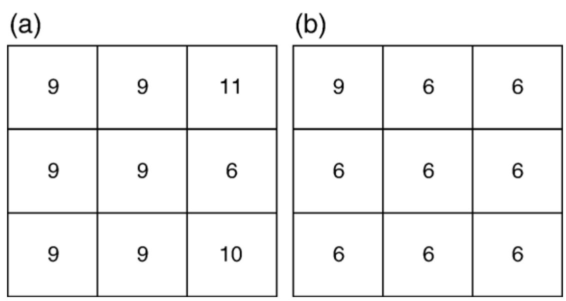

Fig. 13. Same as in Fig. 7, but for New Tamiami Airport (a) and Homestead Air Force Base (b).

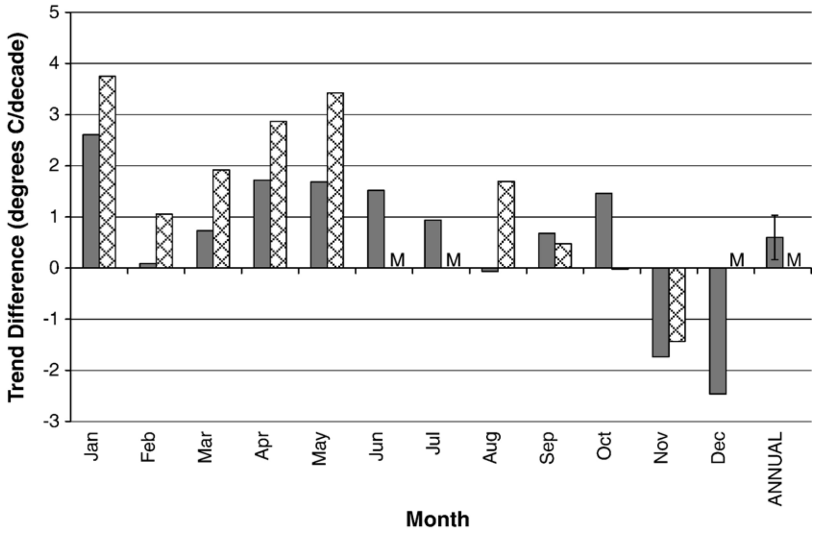

Fig. 14. Same as Fig. 7, but for New Tamiami Airport (grey bars) and Homestead Air Force Base (cross-hatched bars).

not as prominent as they are for many of the other sites considered in this paper.

The 1982–1997 differences between T_E and T trends for the stations we considered (Figs. 8, 10, 12, 14) show that in general, the T_E trends are relatively warmer than the T trends during the growing season, with mixed findings during the non-growing season. The T_E trends are relatively cooler than the T trends during the fall months.

4. Discussion and conclusions

Based on existing problems with documentation of surface station microclimates (Davey and Pielke, 2005) and the complex land-atmosphere interactions that influence the surface energy budgets at these sites including the role of water vapor on the moist enthalpy, T by itself is not sufficient for monitoring near-surface heating trends. Rather, T_E is a more appropriate metric than T, as T_E should be more sensitive to, and thus better depict, contributions to surface heating caused by vegetation and other land cover characteristics. Overall, T_E trends should be larger in magnitude relative to T trends. The physical significance of these differences is due in part to T_E directly accounting not only for dry air temperature (sensible heating) trends but also trends in heating driven by changes of surface and atmospheric moisture. Moist heating effects are implicitly included in T but T by itself is not the total heat content. Trends in T_E add much useful information, relative to trends in T alone, about seasonal cycles in heating trends, particularly regarding growing season versus non-growing season heating trends. Our overall findings that T_E trends were relatively warmer than T trends support our initial expectations as overall trends in both T_E and T (not shown here) were both positive.

It is during the growing season that the differences between T_E and T become most apparent; outside of the growing season, T_E and T values are very similar to each other (Pielke et al., 2004). This observation is borne out in the seasonal variations in differences between T_E and T trends. However, there is a caveat. If T and T_E values are more similar during the non-growing season months, one could expect that the trend magnitudes should also be more similar at these times. This is not what the results are showing. During the fall and winter, there are significant differences between the trends in T_E and the trends in T. This finding leads us to suspect that it is not only annual cycles of vegetation greenup and senescence, but also variations in other quantities such as atmospheric moisture that drive the differences between T_E and T including physical evaporation/sublimation from soils.

The relatively warmer trends in T_E during the spring and summer are not unreasonable and are physically significant. After all, it is during these months that vegetation transpiration is at a maximum. The increased vegetation transpiration during the spring and summer is likely to provide a heating source because of increased near-surface atmospheric moisture. During the fall months, the relatively cooler trends in T_E are of interest. It is not clear why the T_E trends are relatively warmer than T trends for most of the year and then are relatively cooler during the fall months. These findings were repeated in the seasonal trend differences for different land cover types, and also for the individual sites we considered. These findings also are likely to be physically significant, as illustrated by corresponding findings for specific humidity trends. In fact, these findings give support to the idea that land cover exerts a major influence on heating trends (Kalnay and Cai, 2003; Cai and Kalnay, 2004).

It is evident from the individual sites we considered (Figs. 7–14) that local site characteristics, along with regional circulation patterns, do have an influence on the differences between T_E and T trends, both overall and as a function of season. This is as we initially suspected. For example, in Oklahoma City, the finding that T_E trends are relatively warmer than T trends in the spring and summer was especially pronounced for these sites compared to the other sites considered in this work. This finding may be directly tied to the rapid increase in atmospheric moisture and vegetation greenup (and its associated transpiration) which typically occurs in grassland regions during the late spring and early summer. As another example, one may consider the later onset of the relatively warmer T_E trends in the growing season at Minot, North Dakota (Fig. 12). Snow is common in Minot during the winter and early spring, so trends in the presence or absence of snow will presumably have a large influence on the trends in both T and T_E that are observed during the winter and early spring (Strack et al., 2003). The sudden onset of positive $\Delta T_E - \Delta T$ trend differences for June may be caused by the vegetation greenup during the late spring. In Miami, Florida (Fig. 14), the tendency of relative warming in T_E trends seems to occur earlier in the spring, compared to the general patterns observed for the entire surface dataset which indicate that this relative warming begins later into the spring and summer. The seasonal behavior of the heating trend differences in Miami may be related to Miami's subtropical climate and the fact that the overall patterns that have been identified are largely influenced by the patterns observed at sites with more temperate climates, which are more common in the surface dataset used for this study. We must better understand these site microclimates in order to better explain the differences between the T_E and T trends indicated in our analysis. Future work should address, on a region-by-region basis, T_E and T trends as a function of land cover.

The period that was chosen to evaluate trend differences (1982–1997) was dictated primarily by the available dataset for this study, ISWO, which only had data for the years 1982–1997. It would be preferable, of course, to conduct these analyses over a much longer time period in order to assess longer term variability and trends.

We have assumed a constant latent heating term, L, and a constant scale height ($h = 8$ km) in the computations of equivalent temperature. Since both h and L vary slightly with T over the ranges of T encountered in this study, it was concluded that this would only negligibly impact the calculations of equivalent temperature.

Spatial autocorrelation and alternative methods to measure statistical significance were not addressed in this study. These should be a focus of further work on this topic.

Equivalent temperatures are useful for diagnosing spatial variations in heating trends as a function of land cover and reported discrepancies between tropospheric and surface heating trends (Hansen et al., 1995; Hurrell and Trenberth, 1996; Bengtsson et al., 1999) could be at least partially resolved through an investigation of equivalent temperature trends. It would be useful to conduct controlled experiments that change surface moisture and land cover conditions over time and investigate how both T and T_E respond to these changes. Further work should also consider performing a surface energy flux analysis at selected surface sites that measure T and dew point temperature, in an attempt to better understand site microclimates and their possible influences on near-surface temperature and total heat content. Principal components analysis would be useful to identify the different ways, categorized by geographical region and by land cover type, in which land use and land cover can influence near-surface heating trends. A higher-resolution land cover dataset would be useful in this exercise. Any specific sites that show up as outliers within these identified categories could then be targeted for further studies investigating their local microclimates, to better understand how T and T_E are related under these local conditions.

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